

Sensitivity of CUORE to Neutrinoless Double-Beta Decay

F. Alessandria^a, E. Andreotti^{b,c,1}, R. Ardito^d, C. Arnaboldi^e, F. T. Avignone III^f, M. Balata^g, I. Bandac^f,
T. I. Banks^{h,i,g}, G. Bari^j, J. Beeman^k, F. Bellini^{l,m}, A. Bersaniⁿ, M. Biassoni^{e,c}, T. Bloxhamⁱ, C. Brofferio^{e,c},
A. Bryant^{i,h}, C. Bucci^g, X. Z. Cai^o, L. Canonica^{p,n}, S. Capelli^{e,c}, L. Carbone^c, L. Cardani^{l,m}, M. Carrettoni^{e,c},
N. Casali^{l,m}, N. Chott^f, M. Clemenza^{e,c}, C. Cosmelli^{l,m}, O. Cremonesi^c, R. J. Creswick^f, I. Dafinei^m, A. Dally^q,
A. De Biasi^r, M. P. Decowski^{i,h,2}, M. M. Deninno^j, A. de Waard^s, S. Di Domizio^{p,n}, L. Ejzak^{q,*}, R. Faccini^{l,m},
D. Q. Fang^o, H. A. Farach^f, E. Ferri^{e,c}, F. Ferroni^{l,m}, E. Fiorini^c, L. Foggetta^{b,c}, M. A. Franceschi^t, S. J. Freedman^{i,h},
G. Frossati^s, B. K. Fujikawaⁱ, A. Giachero^c, L. Gironi^{e,c}, A. Giuliani^u, P. Gorla^v, C. Gotti^{e,c}, E. Guardincerri^{g,i,3},
T. D. Gutierrez^w, E. E. Haller^{k,x}, K. Hanⁱ, K. M. Heeger^q, H. Z. Huang^y, K. Ichimuraⁱ, R. Kadel^z, K. Kazkaz^{aa},
G. Keppel^r, L. Kogler^{i,h}, Yu. G. Kolomensky^{h,z}, S. Kraft^{e,c}, D. Lenz^q, Y. L. Li^o, X. Liu^y, E. Longo^{l,m}, Y. G. Ma^o,
C. Maiano^{e,c}, G. Maier^d, M. Maino^{1,c}, C. Mancini^{l,m}, C. Martinez^f, M. Martinez^{ab}, R. H. Maruyama^q, N. Mogggi^j,
S. Morganti^m, T. Napolitano^t, S. Newman^{f,g}, S. Nisi^g, C. Nones^{b,c,4}, E. B. Norman^{aa,ac}, A. Nucciotti^{e,c}, F. Orio^m,
D. Orlandi^g, J. L. Ouellet^{h,i}, M. Pallavicini^{p,n}, V. Palmieri^r, L. Pattavina^c, M. Pavan^{e,c}, M. Pedretti^{aa}, G. Pessina^c,
S. Pirro^c, E. Previtali^c, V. Rampazzo^r, F. Rimondi^{ad,j}, C. Rosenfeld^f, C. Rusconi^c, C. Salvioni^{b,c}, S. Sangiorgio^{aa,q,*},
D. Schaeffer^{e,c}, N. D. Scielzo^{aa}, M. Sisti^{e,c}, A. R. Smith^{ae}, F. Stivanello^r, L. Taffarello^{af}, G. Terenziani^r, W. D. Tian^o,
C. Tomei^m, S. Trentalange^y, G. Ventura^{ag,ah}, M. Vignati^{l,m}, B. S. Wang^{aa,ac}, H. W. Wang^o, C. A. Whitten Jr.^{y,5},
T. Wise^q, A. Woodcraft^{ai}, N. Xuⁱ, L. Zanolini^{e,c}, C. Zarra^g, B. X. Zhu^y, S. Zucchelli^{ad,j}

(CUORE Collaboration)

^aINFN - Sezione di Milano, Milano I-20133 - Italy

^bDipartimento di Fisica e Matematica, Università dell'Insubria, Como I-22100 - Italy

^cINFN - Sezione di Milano Bicocca, Milano I-20126 - Italy

^dDipartimento di Ingegneria Strutturale, Politecnico di Milano, Milano I-20133 - Italy

^eDipartimento di Fisica, Università di Milano-Bicocca, Milano I-20126 - Italy

^fDepartment of Physics and Astronomy, University of South Carolina, Columbia, SC 29208 - USA

^gINFN - Laboratori Nazionali del Gran Sasso, Assergi (L'Aquila) I-67010 - Italy

^hDepartment of Physics, University of California, Berkeley, CA 94720 - USA

ⁱNuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720 - USA

^jINFN - Sezione di Bologna, Bologna I-40127 - Italy

^kMaterials Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720 - USA

^lDipartimento di Fisica, Sapienza Università di Roma, Roma I-00185 - Italy

^mINFN - Sezione di Roma, Roma I-00185 - Italy

ⁿINFN - Sezione di Genova, Genova I-16146 - Italy

^oShanghai Institute of Applied Physics (Chinese Academy of Sciences), Shanghai 201800 - China

^pDipartimento di Fisica, Università di Genova, Genova I-16146 - Italy

^qDepartment of Physics, University of Wisconsin, Madison, WI 53706 - USA

^rINFN - Laboratori Nazionali di Legnaro, Legnaro (Padova) I-35020 - Italy

^sKamerlingh Onnes Laboratorium, Leiden University, Leiden, RA 2300 - The Netherlands

^tINFN - Laboratori Nazionali di Frascati, Frascati (Roma) I-00044 - Italy

^uCentre de Spectrométrie Nucléaire et de Spectrométrie de Masse, 91405 Orsay Campus - France

^vINFN - Sezione di Roma Tor Vergata, Roma I-00133 - Italy

^wPhysics Department, California Polytechnic State University, San Luis Obispo, CA 93407 - USA

^xDepartment of Materials Science and Engineering, University of California, Berkeley, CA 94720 - USA

^yDepartment of Physics and Astronomy, University of California, Los Angeles, CA 90095 - USA

^zPhysics Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720 - USA

^{aa}Lawrence Livermore National Laboratory, Livermore, CA 94550 - USA

^{ab}Laboratorio de Fisica Nuclear y Astroparticulas, Universidad de Zaragoza, Zaragoza 50009 - Spain

^{ac}Department of Nuclear Engineering, University of California, Berkeley, CA 94720 - USA

^{ad}Dipartimento di Fisica, Università di Bologna, Bologna I-40127 - Italy

^{ae}EH&S Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720 - USA

^{af}INFN - Sezione di Padova, Padova I-35131 - Italy

^{ag}Dipartimento di Fisica, Università di Firenze, Firenze I-50125 - Italy

^{ah}INFN - Sezione di Firenze, Firenze I-50125 - Italy

^{ai}SUPA, Institute for Astronomy, University of Edinburgh, Blackford Hill, Edinburgh EH9 3HJ - UK

*Corresponding author

Email addresses: ejzak@wisc.edu (L. Ejzak), sangiorgio1@llnl.gov (S. Sangiorgio)

¹Presently at: Joint Research Center, Institute for Reference Materials and Measurements, 2440 Geel - Belgium

²Presently at: Nikhef, 1098 XG Amsterdam - The Netherlands

³Presently at: Los Alamos National Laboratory, Los Alamos, NM 87545 - USA

⁴Presently at: CEA / Saclay, 91191 Gif-sur-Yvette - France

⁵Deceased

Abstract

In this paper, we study the sensitivity of CUORE, a bolometric double-beta decay experiment under construction at the Laboratori Nazionali del Gran Sasso in Italy. Two approaches to the computation of experimental sensitivity are discussed and compared, and the formulas and parameters used in the sensitivity estimates are provided. Assuming a background rate of 10^{-2} cts/(keV kg y), we find that, after 5 years of live time, CUORE will have a 1σ sensitivity to the neutrinoless double-beta decay half-life of $\widehat{T}_{1/2}^{0\nu}(1\sigma) = 1.6 \times 10^{26}$ y and thus a potential to probe the effective Majorana neutrino mass down to 41–95 meV; the sensitivity at 1.64σ , which corresponds to 90% C.L., will be $\widehat{T}_{1/2}^{0\nu}(1.64\sigma) = 9.5 \times 10^{25}$ y. This range is compared with the claim of observation of neutrinoless double-beta decay in ^{76}Ge and the preferred range in the neutrino mass parameter space from oscillation results.

Keywords: neutrino experiment, double-beta decay, sensitivity, bolometer, Poisson statistics

DISCLAIMER: This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

1. Introduction

Neutrinoless double-beta decay ($0\nu\beta\beta$) (see Refs. [1, 2, 3] for recent reviews) is a rare nuclear process hypothesized to occur if neutrinos are Majorana particles. In fact, the search for $0\nu\beta\beta$ is currently the only experimentally feasible method to establish the Majorana nature of the neutrino. The observation of $0\nu\beta\beta$ may also probe the absolute mass of the neutrino and the neutrino mass hierarchy. Many experiments, focusing on several different candidate decay nuclides and utilizing various detector techniques, have sought evidence of this decay [4, 5, 6, 7, 8]; next-generation detectors are currently under development and construction and will begin data taking over the next few years. Evidence of $0\nu\beta\beta$ in ^{76}Ge has been reported [9, 10, 11] but has yet to be confirmed [12, 13, 14, 15].

The Cryogenic Underground Observatory for Rare Events

(CUORE) [16, 17] is designed to search for $0\nu\beta\beta$ in ^{130}Te . Crystals made of natural TeO_2 , with an isotopic abundance of 34.167% of ^{130}Te [18], will be operated as bolometers, serving as source and detector at the same time. Such detectors combine excellent energy resolution with low intrinsic background, and they have been operated in stable conditions underground for several years [19, 20, 21]. Individual detectors can be produced with masses up to ~ 1 kg, allowing for the construction of close-packed large-mass arrays. Bolometric detectors enable precision measurement of the energy spectrum of events inside the crystals, allowing the search for an excess of events above background in a narrow window around the transition energy of the isotope of interest. Such a peak constitutes the signature of $0\nu\beta\beta$, and if it is observed, the $0\nu\beta\beta$ half-life can be determined from the number of observed events.

The current best limit on $0\nu\beta\beta$ in ^{130}Te comes from the Cuoricino experiment [4, 22, 23], which operated 58 crystals of natural TeO_2 and 4 enriched TeO_2 crystals (containing approximately 11 kg of ^{130}Te in total) in the Laboratori Nazionali del Gran Sasso, Italy, from 2003–2008. With a total exposure of 19.75 kg y, Cuoricino set a limit of $T_{1/2}^{0\nu} > 2.8 \times 10^{24}$ y (90% C.L.) [4] on the $0\nu\beta\beta$ half-life of ^{130}Te .

CUORE, the follow-up experiment to Cuoricino, is currently under construction and will exploit the experience and results gained from its predecessor. With its 988 detectors and a mass of ~ 206 kg of ^{130}Te , CUORE will be larger by more than an order of magnitude. Background rates are also expected to be reduced by approximately an order of magnitude with respect to Cuoricino.

In this study, we discuss the sensitivity of CUORE and of CUORE-0, the initial phase of CUORE. We start by providing the detailed assumptions and formulas for the sensitivity estimations. We then review the experimental setup and parameters from which the sensitivity values are calculated. Finally, we compare the sensitivities with the claim of observation of $0\nu\beta\beta$ in ^{76}Ge and the preferred range of neutrino masses from oscillation results.

2. Sensitivity of Double-Beta Decay Experiments

After introducing some basic $0\nu\beta\beta$ formulas in Sec. 2.1, we will present two possible approaches that can be taken to derive an ‘experimental sensitivity’ that expresses the capabilities of an experiment.

In Sec. 2.2, we will develop a simplified, formula-based calculation that uses several basic experimental parameters (e.g., resolution, background rate, mass) to express sensitivity in terms of expected background fluctuations. We will refer to this calculation as the “background-fluctuation” sensitivity. The background-fluctuation sensitivity cannot be extended to the ideal zero-background case, so we develop an analytical expression for zero-background sensitivity in Sec. 2.3.

In Sec. 2.4, we will discuss a procedure to express sensitivity as the average limit that a particular experiment can expect to set in the case that the true $0\nu\beta\beta$ rate is zero, by applying the experiment’s analysis tools to a suite of Monte Carlo trials. We will refer to this calculation as the “average-limit” sensitivity.

As we will show, the results of the two approaches are compatible, although the philosophies of their construction differ.

2.1. Basic Double-Beta Decay Physics

Double-beta decay is a second-order weak process, so half-lives are typically long: two-neutrino double-beta decay half-lives are at least of order 10^{18} years, while current limits on $0\nu\beta\beta$ half-lives are on the order of 10^{24} years or greater. With such long half-lives, the radioactive decay law can be approximated as

$$N(t) \simeq N_0 \left(1 - \ln(2) \cdot \frac{t}{T_{1/2}} \right), \quad (1)$$

where $T_{1/2}$ is the half-life, N_0 is the initial number of atoms and $N(t)$ is the number of atoms left after time t has passed.

Assuming that the exchange of a light Majorana neutrino is the dominant $0\nu\beta\beta$ mechanism, the effective Majorana mass of the electron neutrino can be inferred from the $0\nu\beta\beta$ half-life as follows [2]:

$$m_{\beta\beta} = \frac{m_e}{\sqrt{F_N \cdot T_{1/2}^{0\nu}}}, \quad (2)$$

where m_e is the electron mass, F_N is a nuclear structure factor of merit that includes the nuclear matrix elements (NME) and the phase space of the $0\nu\beta\beta$ transition, and $T_{1/2}^{0\nu}$ is the $0\nu\beta\beta$ half-life.

NMEs are difficult to calculate, and a large range of values can be found in the literature, arising from variations in the details of the models and the assumptions made. For the purpose of this work, we will consider the most recent calculations from three different methods: Quasiparticle Random Phase Approximation (QRPA) (carried out by two different groups: *Faessler et al.*, henceforth denoted

by QRPA-F, and *Suhonen et al.*, henceforth denoted by QRPA-S), Interacting Shell Model (ISM) and Interacting Boson Model (IBM). F_N values and references are shown in Tab. 1. These values are calculated using the NMEs reported by each group and their suggested phase space calculation, taking care to match the values of parameters within each model as pointed out in Ref. [24]. For the QRPA calculations, both groups report several values of the NMEs depending on the choice of the input parameters in the model. Therefore, we quote a range of possible nuclear factors of merit, taking the maximum and minimum value reported by each of the two groups. A range is also shown for the ISM model to account for the choice of different models of short-range correlations. No statistical meaning is implied in the use of these ranges.

2.2. Background-Fluctuation Sensitivity

The mean value S_0 of the $0\nu\beta\beta$ signal, i.e., the expected number of $0\nu\beta\beta$ decays observed during the live time t is:

$$S_0 = \frac{M \cdot N_A \cdot a \cdot \eta}{W} \cdot \ln(2) \cdot \frac{t}{T_{1/2}^{0\nu}} \cdot \varepsilon, \quad (3)$$

where M is the total active mass, η is the stoichiometric coefficient of the $0\nu\beta\beta$ candidate (i.e., the number of nuclei of the candidate $0\nu\beta\beta$ element per molecule of the active mass), W is the molecular weight of the active mass, N_A is the Avogadro constant, a is the isotopic abundance of the candidate $0\nu\beta\beta$ nuclide and ε is the physical detector efficiency.

In Eq. (3), $T_{1/2}^{0\nu}$ refers to the (unknown) *true value* of the $0\nu\beta\beta$ half-life, and S_0 is therefore also unknown. In the derivation of the background-fluctuation sensitivity, we will first determine our sensitivity in terms of a number of counts (analogous to S_0), and then use the form of Eq. (3) to convert to a half-life sensitivity (analogous to $T_{1/2}^{0\nu}$). In order to prevent confusion between sensitivities and true values, hatted quantities (e.g., $\widehat{T_{1/2}^{0\nu}}$, $\widehat{S_0}$) will be used to represent the sensitivities corresponding to the unhatted true values.

An experiment can expect to see a background contribution to the counts acquired in the energy window of interest for the $0\nu\beta\beta$ signal. In the case of a bolometric experiment, or indeed any experiment in which the source is embedded in the detector (common though not universal for $0\nu\beta\beta$ experiments), we can express the mean number of background counts $B(\delta E)$ in an energy window δE as

$$B(\delta E) = b \cdot M \cdot \delta E \cdot t, \quad (4)$$

where b is the background rate per unit detector mass per energy interval (units: cts/(keV kg y)).

In bolometric experiments, b is independently measured, usually by a fit over an energy range much larger than the energy window of interest δE . However, the background in δE still follows a Poisson distribution with a mean value of $B(\delta E)$.

Table 1: $0\nu\beta\beta$ nuclear factors of merit F_N , as defined in Eq. (2), for the candidate $0\nu\beta\beta$ nuclides discussed in this paper, according to different evaluation methods and authors. QRPA: Quasiparticle Random Phase Approximation; ISM: Interacting Shell Model; IBM: Interacting Boson Model. See Sec. 2.1 for details. The phase space values used in calculating F_N values are taken from Table V of Ref. [25] for QRPA-F and table 6 of Ref. [26] for the other models.

| Isotope | $0\nu\beta\beta$ nuclear factor of merit F_N (10^{-13} y^{-1}) | | | |
|-------------------|---|-------------|-------------|------------|
| | QRPA-F [27] | QRPA-S [28] | ISM [29] | IBM-2 [30] |
| ^{130}Te | 2.86 – 10.0 | 2.76 – 7.38 | 1.86 – 2.91 | 6.82 |
| ^{76}Ge | 0.88 – 2.60 | 0.66 – 1.81 | 0.33 – 0.50 | 1.88 |

An important assumption is implied by the form of Eq. (4), namely, that the number of background events scales linearly with the absorber mass of the detector. We will use this simple model for our background-fluctuation sensitivity calculations. However, other cases, most notably surface contaminations, are in fact possible wherein the background might not scale with M . A fully correct treatment of an experiment’s background would require a detailed understanding of the physical distribution of the contaminations that are the source of the background, used as input for Monte Carlo simulations of the specific detector geometry under consideration.

Throughout the background-fluctuation sensitivity derivation, we will use Eq. (3) and Eq. (4) as analytic expressions for the expected numbers of signal and background counts assuming a source-equals-detector experimental configuration, but an analogous estimation is possible for any detector configuration.

With the background $B(\delta E)$ as defined in Eq. (4), we can calculate the number of counts that would represent a positive background fluctuation of a chosen significance level. For simplicity, we construct a single-bin counting experiment wherein the width of the bin is equal to the energy window δE ; this way we need to consider only a single measured value, sampling a count distribution with mean $B(\delta E)$, and we can decouple the sensitivity calculation from the specific analysis approach used by the experiment.

We can now define our background-fluctuation sensitivity: it is the smallest mean signal \widehat{S}_0 that is *greater than or equal to* a background fluctuation of a chosen significance level. It is common in this kind of study [31] to express the significance level in terms of Gaussian standard deviations from the background value. We will speak in general terms of ‘sensitivity at n_σ ’, where n_σ is the desired significance level in terms of number of Gaussian σ . Thus, if $B(\delta E)$ is large enough that the background count distribution can be considered to be Gaussian, the desired value of $\widehat{S}(\delta E)$ is determined by setting the following requirement in terms of $\sigma = \sqrt{B(\delta E)}$:

$$\widehat{S}(\delta E) = \widehat{S}_0 \cdot f(\delta E) = n_\sigma \cdot \sqrt{B(\delta E)}, \quad (5)$$

where $f(\delta E)$ is the fraction of signal events that fall in the energy window cut δE around the Q-value. The inclu-

sion of $f(\delta E)$ arises from our construction of a single-bin counting experiment; it serves as a simple estimate of the analysis efficiency.

For a Gaussian signal (i.e., Gaussian-distributed in energy around the Q-value), the signal fraction $f(\delta E)$ is

$$f(\delta E) = \text{erf} \left(\frac{\delta E}{\Delta E} \cdot \sqrt{\ln(2)} \right), \quad (6)$$

where ΔE is the detector FWHM energy resolution. The value of δE can be chosen to maximize the $\widehat{S}(\delta E)$ -to- $\sqrt{B(\delta E)}$ ratio in the energy window of interest, which in turn optimizes the sensitivity criterion expressed by Eq. (5); this optimal choice corresponds to $\delta E \approx 1.2\Delta E$. It is, however, common to take $\delta E = \Delta E$. In this case, the sensitivity differs by less than 1% from the one calculated at the optimal cut.

By using the expressions for \widehat{S}_0 and $B(\delta E)$ from Eq. (3) and (4), we obtain the Gaussian-regime expression for the background-fluctuation sensitivity of $0\nu\beta\beta$ experiments in the following form:

$$\widehat{T}_{1/2}^{0\nu}(n_\sigma) = \frac{\ln(2)}{n_\sigma} \frac{N_A \cdot a \cdot \eta \cdot \varepsilon}{W} \sqrt{\frac{M \cdot t}{b \cdot \delta E}} \cdot f(\delta E). \quad (7)$$

This equation is extremely useful in evaluating the expected performances of prospective experiments, as it analytically links the experimental sensitivity with the detector parameters. Aside from the inclusion of the signal fraction, it is similar to the familiar ‘factor of merit’ expression used within the $0\nu\beta\beta$ experimental community.

For small numbers of observed events, the Gaussian approximation of Eq. (5) and Eq. (7) does not provide the correct probability coverage, and therefore the meaning of the significance level is not preserved. In fact, the Gaussian approximation for the distribution of the number of observed counts becomes invalid when the *expected number of background counts* is small; if $B(\delta E)$ is less than ~ 24 counts, the Gaussian calculation of a 1σ sensitivity will differ from its Poissonian counterpart (developed below) by 10% or more.

Although the Gaussian limit will possibly still be sufficient for CUORE (see Sec. 4), a more careful calculation might be necessary in the case of a lower background or smaller exposure, or for more sensitive experiments in the

future. We therefore compute the sensitivity by assuming a Poisson distribution of the background counts.

In terms of Poisson-distributed variables, the concept expressed by Eq. (5) becomes [32]

$$\sum_{k=\widehat{S}(\delta E)+B(\delta E)}^{\infty} p_B(k) = \alpha, \quad (8)$$

where α is the Poisson integrated probability that the background distribution alone will cause a given experiment to observe a total number of counts larger than $\widehat{S}(\delta E) + B(\delta E)$. As written, Eq. (8) can be solved only for certain values of α because the left-hand side is a discrete sum. To obtain a continuous equation that preserves the Poisson interpretation of Eq. (8), we exploit the fact that the (discrete) left-hand side of Eq. (8) coincides with the (continuous) normalized lower incomplete gamma function $P(a, x)$ (see page 260 of Ref. [33] for details):

$$P(\widehat{S}(\delta E) + B(\delta E), B(\delta E)) = \alpha. \quad (9)$$

The computation of \widehat{S}_0 from Eq. (9), for given values of $B(\delta E)$ and α , can be achieved numerically. Once \widehat{S}_0 is computed in this way, the corresponding Poisson-regime background-fluctuation sensitivity to the half-life $T_{1/2}^{0\nu}$ for neutrinoless double-beta decay is simply calculated by reversing Eq. (3).

For the remainder of this paper, we will use the Poisson-regime calculation based on Eq. (9) to evaluate our background-fluctuation sensitivity. So that we can continue to indicate the significance level with the familiar n_σ notation instead of the less-intuitive α , however, we will label our sensitivities with the n_σ corresponding to a Gaussian upper-tail probability of α (for example, we will call a background-fluctuation sensitivity calculated with $\alpha = 0.159$ in Eq. (9) a ‘ 1σ sensitivity’).

2.3. Analytical Expression for Zero-Background Sensitivity

It is meaningless to define sensitivity in terms of background fluctuations when $B(\delta E) = 0$; therefore, the background-fluctuation sensitivity calculation cannot be extended to the ideal ‘zero-background’ case. If we wish to develop a formula-based, analysis-decoupled zero-background sensitivity calculation, we can still construct a single-bin counting experiment in the same way as we did for the background-fluctuation sensitivity; however, we must adopt a new method of constructing our sensitivity parameter.

To construct the zero-background sensitivity, we choose to follow the Bayesian limit-setting procedure. Instead of comparing the mean signal value $S(\delta E)$ to the mean background value $B(\delta E)$, we are now obliged to consider $S_{max}(\delta E)$, the upper limit on $S(\delta E)$ in the case that the experiment observes zero counts (i.e., no background *or* signal) in δE during its live time. $S_{max}(\delta E)$ can be evaluated using a Bayesian calculation with a flat signal prior (see Eq. (32.32)–(32.34) of Ref. [31]):

$$\frac{\int_{S=0}^{S_{max}(\delta E)} p_S(0) dS}{\int_{S=0}^{\infty} p_S(0) dS} = \frac{\int_{S=0}^{S_{max}(\delta E)} S^0 e^{-S} dS}{\int_{S=0}^{\infty} S^0 e^{-S} dS} = \frac{\text{C.L.}}{100}, \quad (10)$$

where $p_S(k)$ is the Poisson distribution $p_\mu(k)$ with mean $\mu = S$ and the credibility level C.L. is expressed as a percent. Eq. (10) can be solved analytically for $S_{max}(\delta E)$:

$$S_{max}(\delta E) = S_{max} \cdot f(\delta E) = -\ln\left(1 - \frac{\text{C.L.}}{100}\right), \quad (11)$$

where S_{max} is the inferred upper limit on S_0 . Using S_{max} in place of S_0 in Eq. (3), we obtain

$$\widehat{T_{1/2}^{0\nu}}(\text{C.L.}) = -\frac{\ln(2)}{\ln\left(1 - \frac{\text{C.L.}}{100}\right)} \frac{N_A \cdot a \cdot \eta \cdot \varepsilon}{W} M \cdot t \cdot f(\delta E). \quad (12)$$

For practical purposes, this background-free approximation becomes valid when the expected value of the background is of the order of unity, $B(\delta E) \lesssim 1$ count. It should be stressed that, because the zero-background sensitivity is (by necessity) constructed differently than the background-fluctuation sensitivity, the interpretations of the two do not entirely coincide.

2.4. Average-Limit Sensitivity

The average-limit sensitivity calculation is a Monte-Carlo-based procedure constructed in a similar manner as the zero-background sensitivity presented in the previous section. Following what we have done in [4], the method works as follows:

1. Generate a large number of toy Monte Carlo spectra assuming zero $0\nu\beta\beta$ signal in the fit window (much wider than the $\delta E = \Delta E$ window used for the background-fluctuation sensitivity, in order to utilize the available shape information in the fit).
2. For each Monte Carlo spectrum, perform a binned maximum likelihood fit to the spectrum and extract the associated Bayesian limit with a flat signal prior by integrating the posterior probability density (the same analysis technique used in [22, 23]).
3. Construct the distribution of the limits calculated from the Monte Carlo spectrum, and determine its median.

The average-limit sensitivity method is, in a way, more powerful than the analytical background-fluctuation method because it can in principle take into account subtle and detector-dependent experimental effects, which can be difficult or sometimes impossible to model with analytical formulas. However, because the average-limit approach relies on analysis of statistical ensembles, it lacks the great advantages of clarity and simplicity offered by straightforward formulas. It is clear that the two methods must be (and indeed are, as shown later) essentially equivalent

given the same input parameters, though a minor systematic difference arises because the probability distribution of the limits is not symmetric and the median found with the MC does not coincide with the $\widehat{S}(\delta E)$ computed with Eq. (9).

For a completed experiment like Cuoricino, the experimental parameters (e.g., background rate(s) and shape(s), resolution(s), exposure) used as inputs to the Monte Carlo in step 1 are the real parameters that have been directly measured by the experiment. The average-limit sensitivity is meaningful for a completed experiment that has not seen evidence of a signal because it provides an understanding of how ‘lucky’ the experiment was in the limit it was able to set. To adapt the approach for an upcoming experiment, it is of course necessary to instead use the expected experimental parameters to generate the Monte Carlo spectra in step 1. Calculating the average-limit sensitivity in this way allows for the direct comparison of an upcoming experiment with previously reported experimental limits. The average-limit sensitivity is often also the value $0\nu\beta\beta$ physicists have in mind when they consider the meaning of sensitivity; for example, the GERDA experiment reports a sensitivity calculated in essentially this manner [34], although they choose to report the mean expected limit instead of the median.

3. Validation of the Methods with Cuoricino

Cuoricino [35] achieved the greatest sensitivity of any bolometric $0\nu\beta\beta$ experiment to date and served as a prototype for the CUORE experiment. Cuoricino took data from 2003 to 2008 in the underground facilities of the Laboratori Nazionali del Gran Sasso (LNGS), Italy.

The Cuoricino detector consisted of 62 TeO_2 bolometers with a total mass of 40.7 kg. The majority of the detectors had a size of $5 \times 5 \times 5 \text{ cm}^3$ (790 g) and consisted of natural TeO_2 . The average FWHM resolution for these crystals was $6.3 \pm 2.5 \text{ keV}$ at 2615 keV [4], the nearest strong peak to the $0\nu\beta\beta$ transition energy. Their physical efficiency, which is mostly due to the geometrical effect of beta particles escaping the detector and radiative processes, has been estimated to be $\varepsilon_{phys} = 0.874 \pm 0.011$ [4]. The full details of the crystal types present in the detector array can be found in [4].

The most recent Cuoricino limit was published alongside an average-limit sensitivity. This sensitivity was evaluated as the median of the distribution of 90% C.L. limits extracted from toy Monte Carlo simulations that used the measured detector parameters as inputs, and it was determined to be $\widehat{T}_{1/2}^{0\nu}(90\% \text{ C.L.}) = 2.6 \times 10^{24} \text{ y}$.

Because of the different crystal types present in Cuoricino, if we wish to calculate a background-fluctuation sensitivity for Cuoricino to compare with this average-limit sensitivity, we need to slightly adjust the background-fluctuation calculation presented in Sec. 2.2 to accommodate different parameter values for the different crystal

types. Cuoricino can be considered as the sum of virtual detectors, each representing one of the crystal types during one of two major data-taking periods, called Runs. The detectors’ total exposures, background rates after event selection, physical efficiencies, and average resolutions are reported in Ref. [4], subdivided by crystal type and Run as appropriate. Therefore we can use these reported values to calculate both our expected signal $\widehat{S}(\delta E)$ and expected background $B(\delta E)$ as sums of the contributions from these virtual detectors, then follow the Poisson-regime background-fluctuation sensitivity procedure. If we wish our background-fluctuation sensitivity to be quantitatively comparable to a 90% C.L. average-limit sensitivity, we must choose to calculate the background-fluctuation sensitivity at 1.64σ ($\alpha = 0.051$); indeed, doing so yields $\widehat{T}_{1/2}^{0\nu}(1.64\sigma) = 2.6 \times 10^{24} \text{ y}$, in perfect agreement with the average-limit sensitivity.

Following previously established convention for past bolometric experiments [17, 36], we choose to report background-fluctuation sensitivities at 1σ ($\alpha = 0.159$) for upcoming experiments. For the purpose of illustration, the corresponding background-fluctuation sensitivity for Cuoricino would be $\widehat{T}_{1/2}^{0\nu}(1\sigma) = 4.2 \times 10^{24} \text{ y}$.

Although upcoming CUORE-family experiments have historically shown 1σ background-fluctuation sensitivities, which quantitatively roughly coincide with 68% C.L. average-limit sensitivities, other upcoming $0\nu\beta\beta$ experiments commonly report 90% C.L. sensitivities. To prevent confusion between our sensitivity approach and that commonly used by other $0\nu\beta\beta$ experiments, it is instructive to compare 1.64σ background-fluctuation sensitivities to 90% C.L. average-limit sensitivities for both CUORE and CUORE-0; this comparison appears in Sec. 4.

4. CUORE sensitivity

CUORE will consist of an array of 988 TeO_2 cubic detectors, similar to the $5 \times 5 \times 5 \text{ cm}^3$ Cuoricino crystals described above. The total mass of the detectors will be 741 kg. The detectors will be arranged in 19 individual towers and operated at $\sim 10 \text{ mK}$ in the Gran Sasso underground laboratory. The expected energy resolution FWHM of the CUORE detectors is $\Delta E \approx 5 \text{ keV}$ at the $0\nu\beta\beta$ transition energy, or Q-value ($\sim 2528 \text{ keV}$ for ^{130}Te [37, 38, 39]). This resolution represents an improvement over that seen in Cuoricino and has already been achieved in tests performed in the CUORE R&D facility at LNGS. CUORE is expected to accumulate data for about 5 years of total live time. The experiment is currently being constructed and first data-taking is scheduled for 2014.

The CUORE collaboration plans to operate a single CUORE-like tower in the former Cuoricino cryostat, starting in late 2011. This configuration, named CUORE-0, will validate the assembly procedure and the readiness of

Table 2: Values used in the estimation of the sensitivity of CUORE-0 and CUORE. Symbols are defined in Eq. (3), Eq. (4), and Eq. (5). See Sec. 4 for a discussion of the background values.

| Experiment | a (%) | η | ε (%) | W (g/mol) | M (kg) | ΔE (keV) | $f(\Delta E)$ (%) | b (cts/(keV kg y)) |
|------------|------------|--------|----------------------|----------------|-------------|---------------------|----------------------|-------------------------|
| CUORE-0 | 34.167 | 1 | 87.4 | 159.6 | 39 | 5 | 76 | 0.05 |
| CUORE | 34.167 | 1 | 87.4 | 159.6 | 741 | 5 | 76 | 0.01 |

the background reduction measures. The experimental parameters of CUORE-0 and CUORE that are used in the sensitivity calculations are summarized in Tab. 2.

The background rate is the most critical parameter to assess before the calculation of the sensitivity can be carried out.

In Cuoricino, the average background counting rate in the region of interest (ROI) for $0\nu\beta\beta$ decay, namely, a region centered at the Q-value and 60 keV wide, was 0.161 ± 0.006 cts/(keV kg y) for the $5 \times 5 \times 5$ cm³ crystals⁶. An analysis of the background sources responsible for the flat background in the ROI has been performed on a partial set of statistics [17, 23], following the technique and the model developed for the MiDBD experiment [40]. The result of this analysis was the identification of three main contributions: $30 \pm 10\%$ of the measured flat background in the ROI is due to multi-Compton events due to the 2615 keV gamma ray from the decay chain of ²³²Th from the contamination of the cryostat shields; $10 \pm 5\%$ is due to surface contamination of the TeO₂ crystals with ²³⁸U and ²³²Th (primarily degraded alphas from these chains); and $50 \pm 20\%$ is ascribed to similar surface contamination of inert materials surrounding the crystals, most likely copper (other sources that could contribute are muons [41] and neutrons, but simulations indicate that these have only a minor effect).

On the basis of this result, the R&D for CUORE has pursued two major complementary avenues: one, the reduction of surface contamination, and two, the creation of an experimental setup in which potential background contributions are minimized by the selection of extremely radio-pure construction materials and the use of highly efficient shields. The latter activity is based mainly on standard procedures (material selection with HPGe spectroscopy, underground storage to avoid activation, evaluation of the background suppression efficiencies of the shields on the basis of Monte Carlo simulations [42], etc.). However, the required surface contamination levels are extremely low, on the order of 1–10 nBq/cm², nearly undetectable with any standard technique used in surface analysis. In most cases, only bolometric detectors are sufficiently sensitive; at this time, our understanding of these

contaminations comes only from the statistics-limited data sets collected by small test detectors constructed from CUORE materials (see Ref. [43] for the contract requirements on and measurements of the contamination levels of the crystals).

A detailed analysis of the background mitigation effort and its extrapolation to the CUORE and CUORE-0 background is out of the scope of the present paper. A full account of the performed measurements, analysis, and results is being prepared and will be published soon. Here, to justify the expected background rates that will be used for the sensitivity estimations, we offer a brief summary, allowing us to perform a simple scaling to obtain the range into which we expect the CUORE-0 background rate to fall and support the conclusion that CUORE will meet its design background specification.

CUORE crystals are produced following a controlled protocol [44] that is able to ensure a bulk contamination level lower than 3×10^{-12} g/g in both ²³⁸U and ²³²Th. A more rigorous surface-treatment technique than that used for the Cuoricino crystals was developed; when studied with a small array of bolometric detectors, it proved to be able to reduce the surface contamination of Cuoricino crystals re-treated with this method by approximately a factor of 4 [45]. The technique has now been adopted and applied in the production of the CUORE crystals, and bolometric tests have already proven its efficacy [43]. A preliminary evaluation of the surface contaminations of the final CUORE crystals [44] indicated a lower limit on the reduction with respect to the contamination seen in Cuoricino of a factor of 2; the measurement was statistics-limited, so the true reduction factor may be greater.

In Cuoricino, a large fraction of the $0\nu\beta\beta$ background was identified as due to surface contamination of the copper — the only significant material surrounding the detectors, which are mounted in vacuum. Unfortunately, the signature of the surface contamination of the copper is extremely weak when compared to other contributions, as the background ascribed to the copper contamination is a flat continuum that can be easily observed only in the peakless 3–4 MeV region of the spectrum [40, 45]. Extensive efforts have been dedicated to the study of different treatment procedures able to reduce the copper surface contamination; in the end, a technique that proved to be capable of reducing the copper surface contamination by at least a factor of 2 as compared with that observed in Cuoricino has been selected by the collaboration as the

⁶This is the background rate measured when operating the array in anticoincidence; this evaluation is extracted from the $0\nu\beta\beta$ best fit [4] and corrected for the instrumental efficiency to give the real rate.

baseline for the CUORE copper treatment.

Based on the above-reported considerations, we may define a conservative case wherein we assume that the specific contaminations of the CUORE copper and crystals have both been reduced by a factor of 2 relative to Cuoricino. There is a good chance that the reduction factors are much higher, but this cannot be confirmed at present due to the limited statistics of our measurements. Only CUORE-0 will ultimately be able to measure the true level of radiopurity achieved with the chosen surface treatment.

CUORE-0 will consist of CUORE crystals mounted in CUORE-style frames as a single tower. Because of this geometry, which is similar to that of Cuoricino, the contamination reduction factors reported above scale almost directly to the background we expect to observe in the ROI. The total amount of copper facing the crystals will be only slightly reduced with respect to Cuoricino, but its surface will be treated with the new procedure studied for CUORE. CUORE-0 will be assembled in the Cuoricino cryostat, so the gamma background from contamination in the cryostat shields will remain approximately the same as in Cuoricino. We consider that the irreducible background for CUORE-0 comes from the 2615 keV ^{208}Tl line due to ^{232}Th contaminations in the cryostat, in the case that all other background sources (i.e., surface contaminations) have been rendered negligible; this would imply a lower limit of ~ 0.05 cts/(keV kg y) on the expected background in CUORE-0. Similarly, an upper limit of 0.11 cts/(keV kg y) follows from scaling the Cuoricino background in the conservative case, described above, of a factor of 2 improvement in crystal and copper contamination.

A plot of the expected 1σ background-fluctuation sensitivity of CUORE-0 as a function of live time in these two bounding cases is shown in Fig. 1. Tab. 3 provides a quantitative comparison between 1σ background-fluctuation sensitivities (as shown in Fig. 1), 1.64σ background-fluctuation sensitivities, and 90% C.L. average-limit sensitivities for CUORE-0 at several representative live times. The anticipated total live time of CUORE-0 is approximately two years; for this live time at the 0.05 cts/(keV kg y) background level, $B(\delta E) \sim 20$ cts, meaning that the Poisson-regime calculation is really necessary in this case because it differs from the Gaussian-regime approximation by $> 10\%$ (see Sec. 2.2).

CUORE, in addition to the new crystals and frames already present in CUORE-0, will be assembled as a 19-tower array in a newly constructed cryostat. The change in detector geometry will have two effects. First, the large, close-packed array will enable significant improvement in the anticoincidence analysis, further reducing crystal-related backgrounds. Second, the fraction of the total crystal surface area facing the outer copper shields will be reduced by approximately a factor of 3. In addition to these considerations, the new cryostat will contain thicker lead shielding and be constructed of cleaner material, which should result in a gamma background approximately an order of magni-

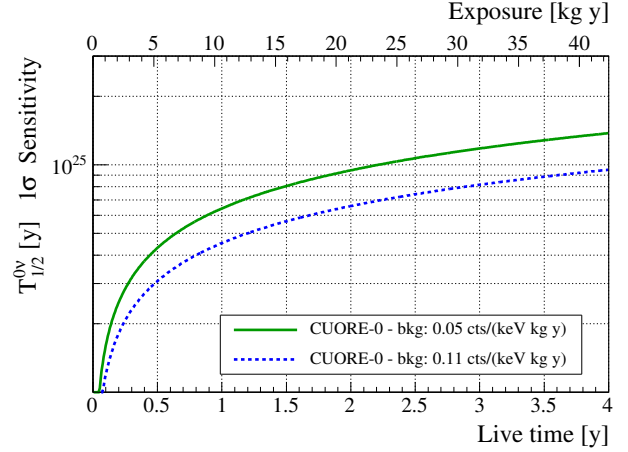


Figure 1: CUORE-0 background-fluctuation sensitivity at 1σ for two different values of the background rate in the region of interest, 0.05 cts/(keV kg y) (solid line) and 0.11 cts/(keV kg y) (dotted line), representing the range into which the CUORE-0 background is expected to fall.

tude lower than that in the Cuoricino cryostat. Based on the above considerations and the Cuoricino results, CUORE is expected to achieve its design background value of 0.01 cts/(keV kg y). A comprehensive Monte Carlo simulation that includes the most recent background measurements is currently ongoing.

An overview of the 1σ background-fluctuation sensitivities of the Cuoricino, CUORE-0, and CUORE TeO_2 bolometric experiments is shown in Fig. 2. The Cuoricino 1σ sensitivity calculated in Sec. 3 is shown for reference. A 1σ half-life sensitivity close to 10^{25} years is expected from 2 years' live time of CUORE-0. Once CUORE starts data-taking, another order of magnitude improvement in sensitivity is expected in another two years.

A plot of the CUORE experiment's sensitivity as a function of the live time and exposure is shown in Fig. 3. Tab. 4 provides a quantitative comparison between 1σ background-fluctuation sensitivities (as shown in Fig. 3), 1.64σ background-fluctuation sensitivities, and 90% C.L. average-limit sensitivities for CUORE at several representative live times. The anticipated total live time of CUORE is approximately five years; for this live time at the design goal background level, $B(\delta E) \sim 190$ cts, meaning that the Gaussian approximation would still be valid in this case. The sensitivity values we show in this paper nevertheless differ from those previously reported by the experiment [16, 17], but this $\sim 25\%$ difference can be attributed to the inclusion of the signal fraction $f(\delta E)$, which has not previously been considered.

As mentioned previously, estimates of the CUORE background are currently based on measured limits, not measured values. While there are promising indications that it may perform even better than its design value of 0.01 cts/(keV kg y), it is also likely that background rates of 0.001 cts/(keV kg y) or below cannot be reached with the present technology. Even so, R&D activities are al-

Table 3: Background-fluctuation half-life sensitivities at 1σ for CUORE-0 under different background estimations after one, two, and four years of live time. The bolded column corresponds to the approximate anticipated total live time of two years. 1.64σ background-fluctuation sensitivities and 90% C.L. average-limit sensitivities, in italics, are also provided to illustrate the similarity of the two values.

| b (cts/(keV kg y)) | ΔE (keV) | Method (sig./conf. level) | half-life sensitivity (10^{25} y) | | |
|-------------------------|---------------------|------------------------------|---|--------------------|-------------|
| | | | 1 y | 2 y | 4 y |
| 0.11 | 5 | 1σ | 0.45 | 0.66 | 0.95 |
| | | 1.64σ | <i>0.28</i> | <i>0.40</i> | <i>0.58</i> |
| | | 90% C.L. | <i>0.29</i> | <i>0.41</i> | <i>0.59</i> |
| 0.05 | 5 | 1σ | 0.64 | 0.94 | 1.4 |
| | | 1.64σ | <i>0.39</i> | <i>0.58</i> | <i>0.84</i> |
| | | 90% C.L. | <i>0.39</i> | <i>0.59</i> | <i>0.83</i> |

Table 4: Background-fluctuation half-life sensitivities at 1σ for CUORE after two, five, and ten years of live time. The bolded column corresponds to the approximate anticipated total live time of five years. The sensitivities are reported for the design goal background level, as well as for an order-of-magnitude improvement over the design goal. 1.64σ background-fluctuation sensitivities and 90% C.L. average-limit sensitivities, in italics, are also provided to illustrate the similarity of the two values.

| b (cts/(keV kg y)) | ΔE (keV) | Method (sig./conf. level) | half-life sensitivity (10^{26} y) | | |
|-------------------------|---------------------|------------------------------|---|--------------------|------------|
| | | | 2 y | 5 y | 10 y |
| 0.01 | 5 | 1σ | 0.97 | 1.6 | 2.2 |
| | | 1.64σ | <i>0.59</i> | <i>0.95</i> | <i>1.4</i> |
| | | 90% C.L. | <i>0.59</i> | <i>0.97</i> | <i>1.4</i> |
| 0.001 | 5 | 1σ | 2.7 | 4.6 | 6.7 |
| | | 1.64σ | <i>1.7</i> | <i>2.8</i> | <i>4.1</i> |
| | | 90% C.L. | <i>1.6</i> | <i>2.8</i> | <i>4.2</i> |

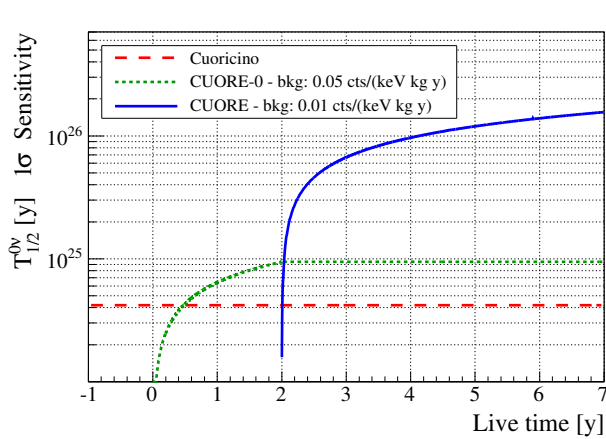


Figure 2: 1σ expected background-fluctuation sensitivities for the CUORE-0 (dotted line) and CUORE (solid line) experiments, calculated from Eq. (9) and Eq. (3) with the experimental parameters shown in Tab. 2. The Cuoricino 1σ sensitivity calculation (dashed line) is discussed in Sec. 3.

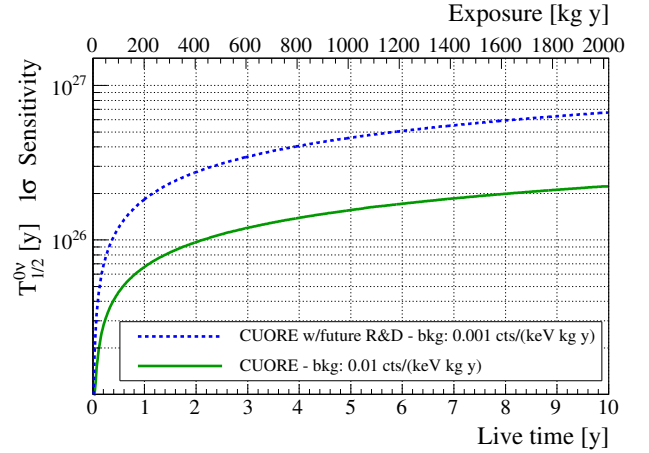


Figure 3: Baseline expected background-fluctuation sensitivity of the CUORE experiment at 1σ (solid line). The sensitivity for an order-of-magnitude improvement over the baseline background is also shown (dotted line).

ready underway pursuing ideas for further reduction of the background in a possible future experiment. Techniques for active background rejection are being investigated [46, 47]) that could provide substantial reduction of the background. Sensitivities for a scenario with 0.001 cts/(keV kg y) in a CUORE-like experiment are given in Fig. 3 and Tab. 4.

5. Comparison with the claim in ^{76}Ge

It is interesting to compare the CUORE-0 and CUORE sensitivities with the claim for observation of $0\nu\beta\beta$ in ^{76}Ge [9, 10, 11]. The authors of this claim have reported several different values for the half-life of ^{76}Ge , depending upon the specifics of the analysis; the longest of these, and thus the one requiring the greatest sensitivity to probe, is $T_{1/2}^{0\nu}(^{76}\text{Ge}) = 2.23_{-0.31}^{+0.44} \times 10^{25}$ y [11]. From Eq. (2), it follows that

$$T_{1/2}^{0\nu}(^{130}\text{Te}) = \frac{F_N(^{76}\text{Ge})}{F_N(^{130}\text{Te})} \cdot T_{1/2}^{0\nu}(^{76}\text{Ge}).$$

However, because of the wide spread in F_N calculations (see Tab. 1), directly using this equation to estimate the expected half-life for the $0\nu\beta\beta$ of ^{130}Te can be misleading. A method of treating NME uncertainties based on the QRPA-F calculations is suggested, and shown to be roughly consistent with the QRPA-S and ISM calculations, in [25]. Following this method, the expected 1σ range of $T_{1/2}^{0\nu}(^{130}\text{Te})$ is $(5.1 - 7.1) \times 10^{24}$ y (for the best-fit value of the ^{76}Ge claim) or $(4.2 - 8.9) \times 10^{24}$ y (when the 1σ uncertainty on the ^{76}Ge claim is also included, slightly shifting the central value of the $\log_{10}[T_{1/2}^{0\nu}(^{76}\text{Ge})]$ range as done in [25] so that the errors become symmetric).

The mathematical framework of the background-fluctuation sensitivity calculation can be inverted to determine the magnitude of the mean signal in terms of n_σ that an assumed ‘true’ half-life value will produce in an experiment. Fig. 4 shows the n_σ significance level at which CUORE-0 can probe the ^{76}Ge claim as it accrues statistics over its anticipated live time. The width of the inner band corresponds to the 1σ range of NMEs determined in [25], while the outer band includes the uncertainty on the claim as well; i.e., each band is bounded by curves corresponding to the maximum and minimum $T_{1/2}^{0\nu}(^{130}\text{Te})$ of its respective range, as given above. As can be deduced from the plot, CUORE-0 will achieve at least a 1σ sensitivity to any signal within the expected 1σ range of $T_{1/2}^{0\nu}(^{130}\text{Te})$ within two years. By combining data from CUORE-0 and Cuoricino, the claim could be verified in a shorter time with higher sensitivity.

Thanks to the increased size and lower background, if the ^{130}Te $0\nu\beta\beta$ half-life indeed falls in the 1σ range implied by the claim in ^{76}Ge , CUORE will already be able to achieve a 5σ expected signal above background within about six months.

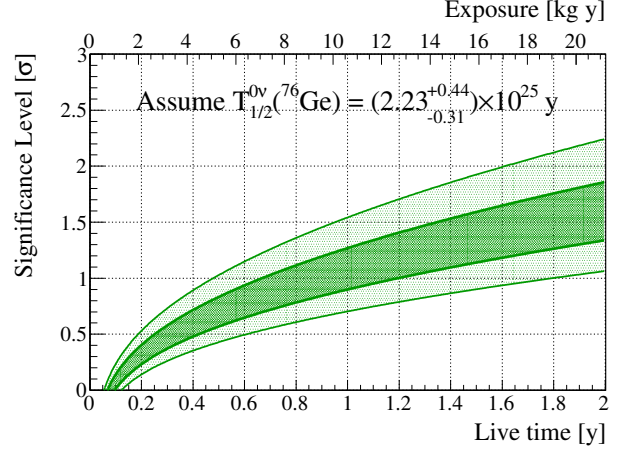


Figure 4: Significance level at which CUORE-0 can observe a signal corresponding to the ^{76}Ge claim, assuming the best expected background of 0.05 cts/(keV kg y). The inner band assumes the best-fit value of the ^{76}Ge claim, and its width arises from the 1σ range of QRPA-F NMEs calculated in [25]. The outer band accounts for the 1σ uncertainty on the ^{76}Ge claim in addition to the range of NMEs.

6. Conclusions

In recent years, experimenters have made great strides in the search for neutrinoless double-beta decay, a discovery which would establish the Majorana nature of the neutrino and have far-reaching ramifications in physics. Next-generation $0\nu\beta\beta$ experiments like CUORE have two primary goals: to test the claim of observation of $0\nu\beta\beta$ in ^{76}Ge , and to begin to probe effective neutrino masses of $m_{\beta\beta} \leq 50$ meV (commonly referred to as the ‘inverted hierarchy region’ of the neutrino mass phase space). We have investigated the expected performance of CUORE, allowing evaluation of its ability to meet these two goals.

In Sec. 2, we developed two different approaches to calculating experimental sensitivity: the background-fluctuation sensitivity and the average-limit sensitivity. The background-fluctuation sensitivity parametrizes the signal that the experiment is capable of observing in terms of the expected background fluctuations, while the average-limit sensitivity is the average limit that the experiment expects to set in the case that there is no signal to find. Although the average-limit sensitivity is more directly comparable to previously reported limits by construction, we prefer to evaluate upcoming experiments in terms of the background-fluctuation sensitivity because the goal of $0\nu\beta\beta$ experiments is to discover and measure neutrinoless double beta decay, not merely set a limit. In fact, the two methods produce quantitatively similar results, so it is not misleading to consider the background-fluctuation sensitivity as an approximation of the average-limit sensitivity if the significance/credibility levels of the two methods are properly chosen to coincide.

Tab. 5 contains a summary of 1σ background-fluctuation sensitivities to the neutrino Majorana mass according to different NME calculations, assuming that the exchange

of a light Majorana neutrino is the dominant $0\nu\beta\beta$ mechanism, as discussed in Sec. 2.1. These values are considered the official sensitivity values for CUORE-family experiments. During its run, CUORE will fully explore the ^{130}Te $0\nu\beta\beta$ half-life range corresponding to the claim of observation of $0\nu\beta\beta$ in ^{76}Ge .

For illustrative purposes, Tab. 5 also shows the limiting “zero-background” case for both CUORE-0 and CUORE. The calculation is performed at 68% C.L. so that the values can be considered as zero-background extrapolations of the finite-background 1σ background-fluctuation sensitivities. CUORE-0 and CUORE will both have sufficiently good resolution that the signal fraction may be omitted from Eq. (12) for the calculation. As discussed in Sec. 2.3, the zero-background approximation applies when $B(\delta E) \lesssim 1$ count; we can determine the background rate that each experiment would have to achieve to fulfill this requirement from Eq. (4), assuming a window of $\delta E = 2.5\Delta E$ (large enough that including $f(\delta E)$ would not change the values reported in Tab. 5). CUORE-0 would require $b \lesssim 1.0 \times 10^{-3}$ cts/(keV kg y); CUORE would require $b \lesssim 2.2 \times 10^{-5}$ cts/(keV kg y), nearly three orders of magnitude better than the baseline background rate.

In Fig. 5, the expected sensitivity of CUORE is compared with the preferred values of the neutrino mass parameters obtained from neutrino oscillation experiments. The sensitivity of CUORE will allow the investigation of the upper region of the effective Majorana neutrino mass phase space corresponding to the inverted hierarchy of neutrino masses.

Acknowledgments

The CUORE Collaboration thanks the Directors and Staff of the Laboratori Nazionali del Gran Sasso and the technical staffs of our Laboratories. This work was supported by the Istituto Nazionale di Fisica Nucleare (INFN); the Director, Office of Science, of the U.S. Department of Energy under Contract Nos. DE-AC02-05CH11231 and DE-AC52-07NA27344; the DOE Office of Nuclear Physics under Contract Nos. DE-FG02-08ER41551 and DEFG03-00ER41138; the National Science Foundation under Grant Nos. NSF-PHY-0605119, NSF-PHY-0500337, NSF-PHY-0855314, and NSF-PHY-0902171; the Alfred P. Sloan Foundation; and the University of Wisconsin Foundation.

- [1] S. R. Elliott, P. Vogel, Double beta decay, *Ann. Rev. Nucl. Part. Sci.* 52 (2002) 115–151.
- [2] F. T. Avignone, S. R. Elliott, J. Engel, Double beta decay, Majorana neutrinos, and neutrino mass, *Rev. Mod. Phys.* 80 (2008) 481–516.
- [3] A. S. Barabash, Double-beta decay: Present status, *Phys. Atom. Nucl.* 73 (2010) 162–178.
- [4] E. Andreotti, et al. (CUORICINO Collaboration), ^{130}Te Neutrinoless Double-Beta Decay with CUORICINO, *Astropart. Phys.* 34 (2011) 822–831.
- [5] H. V. Klapdor-Kleingrothaus, et al., Latest Results from the Heidelberg-Moscow Double Beta Decay Experiment, *Eur. Phys. J. A* 12 (2001) 147–154.
- [6] C. E. Aalseth, et al. (IGEX Collaboration), IGEX ^{76}Ge neutrinoless double-beta decay experiment: Prospects for next generation experiments, *Phys. Rev. D* 65 (2002) 092007.
- [7] R. Bernabei, et al., Investigation of $\beta\beta$ decay modes in ^{134}Xe and ^{136}Xe , *Phys. Lett. B* 546 (2002) 23–28.
- [8] R. Arnold, et al., First Results of the Search for Neutrinoless Double-Beta Decay with the NEMO 3 Detector, *Phys. Rev. Lett.* 95 (2005) 182302.
- [9] H. V. Klapdor-Kleingrothaus, A. Dietz, H. L. Harney, I. V. Krivosheina, Evidence for neutrinoless double beta decay, *Mod. Phys. Lett. A* 16 (2001) 2409–2420.
- [10] H. V. Klapdor-Kleingrothaus, A. Dietz, I. V. Krivosheina, O. Chkvorets, Data Acquisition and Analysis of the ^{76}Ge Double Beta Experiment in Gran Sasso 1990-2003, *Nucl. Instrum. Meth. A* 522 (2004) 371–406.
- [11] H. V. Klapdor-Kleingrothaus, I. V. Krivosheina, The evidence for the observation of $0\nu\beta\beta$ decay: The identification of $0\nu\beta\beta$ events from the full spectra, *Mod. Phys. Lett. A* 21 (2006) 1547–1566.
- [12] C. E. Aalseth, et al., Comment on ‘Evidence for neutrinoless double beta decay’, *Mod. Phys. Lett. A* 17 (2002) 1475–1478.
- [13] H. L. Harney, Reply to the comment on ‘Evidence for neutrinoless double beta decay’. (*Mod. Phys. Lett. A* 16(2001) 2409), arXiv hep-ph/0205293 (2001).
- [14] F. Feruglio, A. Strumia, F. Vissani, Neutrino oscillations and signals in β and $0\nu2\beta$ experiments, *Nucl. Phys. B* 637 (2002) 345–377.
- [15] A. M. Bakalyarov, A. Y. Balysh, S. T. Belyaev, V. I. Lebedev, S. V. Zhukov, Results of the experiment on investigation of ^{76}Ge double beta decay, *Phys. Part. Nucl. Lett.* 2 (2005) 77–81.
- [16] C. Arnaboldi, et al. (CUORE Collaboration), CUORE: A cryogenic underground observatory for rare events, *Nucl. Instrum. Meth. A* 518 (2004) 775–798.
- [17] R. Ardito, et al. (CUORE Collaboration), CUORE: A cryogenic underground observatory for rare events, arXiv hep-ex/0501010 (2005).
- [18] M. A. Fehr, M. Rehkämper, A. N. Halliday, Application of MC-ICPMS to the precise determination of tellurium isotope compositions in chondrites, iron meteorites and sulfides, *Int. J. Mass Spectrom.* 232 (2004) 83–94.
- [19] A. Alessandrello, et al., A search for neutrinoless double beta decay of ^{130}Te with a thermal detector, *Phys. Lett. B* 285 (1992) 176–182.
- [20] A. Alessandrello, et al., First tests on a large mass, low temperature array detector, *Nucl. Instrum. Meth. A* 360 (1995) 363–366. Proceedings of the Sixth Pisa Meeting on Advanced Detectors.
- [21] A. Alessandrello, et al., Preliminary results on double beta decay of ^{130}Te with an array of twenty cryogenic detectors, *Phys. Lett. B* 433 (1998) 156–162.
- [22] C. Arnaboldi, et al., New Limit on the Neutrinoless $\beta\beta$ Decay of ^{130}Te , *Phys. Rev. Lett.* 95 (2005) 142501.
- [23] C. Arnaboldi, et al. (CUORICINO Collaboration), Results from a search for the $0\nu\beta\beta$ -decay of ^{130}Te , *Phys. Rev. C* 78 (2008) 035502.
- [24] S. T. Cowell, Scaling factor inconsistencies in neutrinoless double beta decay, *Phys. Rev. C* 73 (2006) 028501.
- [25] A. Faessler, et al., Quasiparticle random phase approximation uncertainties and their correlations in the analysis of $0\nu\beta\beta$ decay, *Phys. Rev. D* 79 (2009) 053001.
- [26] J. Suhonen, O. Civitarese, Weak-interaction and nuclear-structure aspects of nuclear double beta decay, *Phys. Rept.* 300 (1998) 123–214.
- [27] F. Simkovic, A. Faessler, V. Rodin, P. Vogel, J. Engel, Anatomy of the $0\nu\beta\beta$ nuclear matrix elements, *Phys. Rev. C* 77 (2008) 045503.
- [28] O. Civitarese, J. Suhonen, Nuclear matrix elements for double beta decay in the QRPA approach: A critical review, *J. Phys. Conf. Ser.* 173 (2009) 012012.
- [29] J. Menendez, A. Poves, E. Caurier, F. Nowacki, Disassembling the nuclear matrix elements of the neutrinoless $\beta\beta$ decay, *Nucl. Phys. A* 818 (2009) 139–151.

Table 5: Summary table of expected parameters and 1σ background-fluctuation sensitivity in half-life and effective Majorana neutrino mass. The different values of $m_{\beta\beta}$ depend on the different NME calculations; see Sec. 2.1 and Tab. 1. Zero-background sensitivities, in italics, are also provided as an estimation of the ideal limit of the detectors' capabilities; they are presented at 68% C.L. so that they can be considered as approximate extrapolations of the 1σ background-fluctuation sensitivities.

| Setup | t (y) | b (cts/(keV kg y)) | $\widehat{T}_{1/2}^{0\nu}(1\sigma)$ (y) | $m_{\beta\beta}$ (meV) | | | |
|----------------|------------|-------------------------|--|---------------------------|---------------|----------------|-----------|
| | | | | QRPA-F | QRPA-S | ISM | IBM |
| CUORE-0 | 2 | 0.05 | 9.4×10^{24} | 170–310 | 190–320 | 310–390 | 200 |
| | | | <i>zero-bkg. case at 68% C.L.: 5.3×10^{25}</i> | <i>70–130</i> | <i>81–130</i> | <i>130–160</i> | <i>85</i> |
| CUORE baseline | 5 | 0.01 | 1.6×10^{26} | 41–77 | 48–78 | 76–95 | 50 |
| | | | <i>zero-bkg. case at 68% C.L.: 2.5×10^{27}</i> | <i>10–19</i> | <i>12–19</i> | <i>19–24</i> | <i>12</i> |

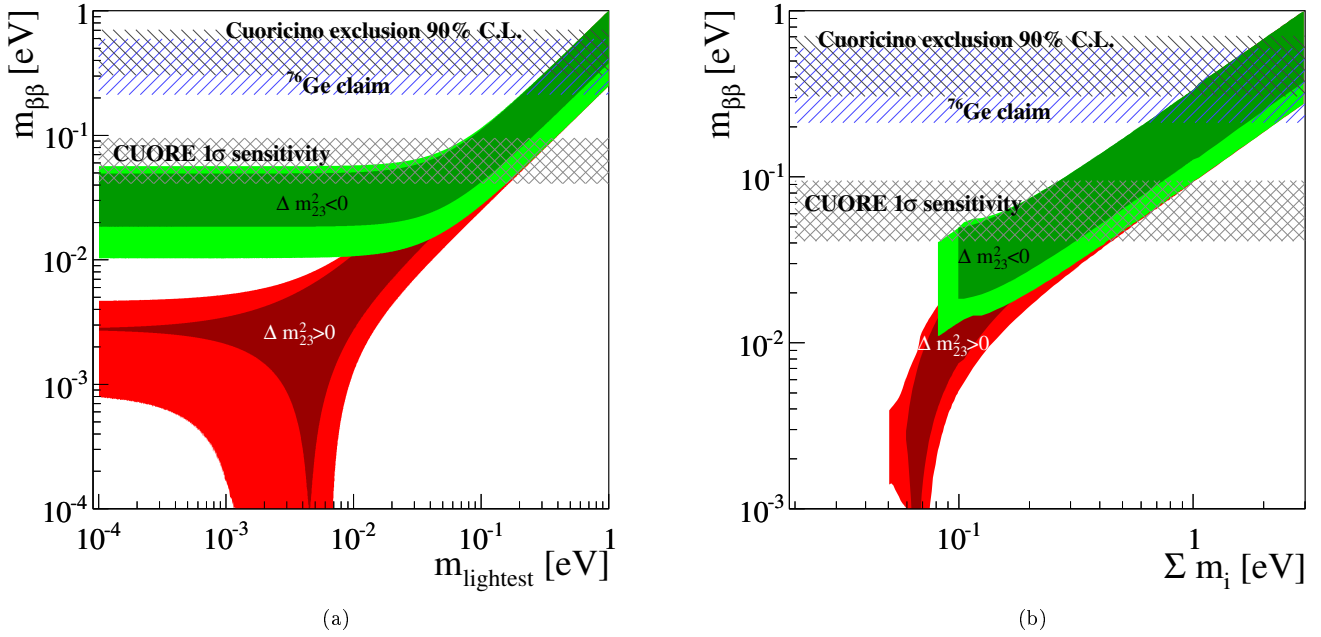


Figure 5: The Cuoricino result and the expected CUORE 1σ background-fluctuation sensitivity overlaid on plots that show the bands preferred by neutrino oscillation data (inner bands represent best-fit data; outer bands represent data allowing 3σ errors) [48]. Both normal ($\Delta m_{23}^2 > 0$) and inverted ($\Delta m_{23}^2 < 0$) neutrino mass hierarchies are shown. (a) The coordinate plane represents the parameter space of $m_{\beta\beta}$ and $m_{lightest}$, following the plotting convention of [48]. (b) The coordinate plane represents the parameter space of $m_{\beta\beta}$ and Σm_i , following the plotting convention of [49]. The widths of the Cuoricino and CUORE bands are determined by the maximum and minimum values of $m_{\beta\beta}$ obtained from the four NME calculations considered in this work.

- [30] J. Barea, F. Iachello, Neutrinoless double- β decay in the microscopic interacting boson model, *Phys. Rev. C* **79** (2009) 044301.
- [31] C. Amsler, et al. (Particle Data Group), Review of particle physics, *Phys. Lett. B* **667** (2008) 1.
- [32] J. J. Hernández, S. Navas, P. Rebecchi, Discovery limits in prospective studies, *Nucl. Instrum. Meth. A* **372** (1996) 293–296.
- [33] M. Abramowitz, I. A. Stegun, *Handbook of Mathematical Functions*, Courier Dover Publications, 1972.
- [34] A. Caldwell, K. Kröninger, Signal discovery in sparse spectra: A Bayesian analysis, *Phys. Rev. D* **74** (2006) 092003.
- [35] C. Arnaboldi, et al., First results on neutrinoless double beta decay of ^{130}Te with the calorimetric CUORICINO experiment, *Phys. Lett. B* **584** (2004) 260–268.
- [36] C. Arnaboldi, et al. (CUORE Collaboration), Physics potential and prospects for the CUORICINO and CUORE experiments, *Astropart. Phys.* **20** (2003) 91–110.
- [37] M. Redshaw, B. J. Mount, E. G. Myers, F. T. Avignone, III, Masses of ^{130}Te and ^{130}Xe and double- β -decay Q -value of ^{130}Te , *Phys. Rev. Lett.* **102** (2009) 212502.
- [38] N. D. Scielzo, et al., Double- β -decay Q values of ^{130}Te , ^{128}Te , and ^{120}Te , *Phys. Rev. C* **80** (2009) 025501.
- [39] S. Rahaman, et al., Double-beta decay Q values of ^{116}Cd and ^{130}Te , *Phys. Lett. B* (2011). Accepted and now in press, doi:10.1016/j.physletb.2011.07.078.
- [40] C. Bucci, et al., Background study and Monte Carlo simulations for large-mass bolometers, *Eur. Phys. J. A* **41** (2009) 155–168.
- [41] E. Andreotti, et al. (CUORICINO Collaboration), Muon-induced backgrounds in the CUORICINO experiment, *Astropart. Phys.* **34** (2010) 18–24.
- [42] F. Bellini, et al., Monte Carlo evaluation of the external gamma, neutron and muon induced background sources in the CUORE experiment, *Astropart. Phys.* **33** (2010) 169–174.
- [43] F. Alessandria, et al. (CUORE Collaboration), CUORE crystal validation runs: results on radioactive contamination and extrapolation to CUORE background (2011). Submitted to *Astroparticle Physics*, arXiv:1108.4757 [nucl-ex].
- [44] C. Arnaboldi, et al., Production of high purity TeO_2 single crystals for the study of neutrinoless double beta decay, *J. Cryst. Growth* **312** (2010) 2999–3008.
- [45] M. Pavan, et al., Control of bulk and surface radioactivity in bolometric searches for double-beta decay, *Eur. Phys. J. A* **36** (2008) 159–166.
- [46] L. Foggetta, A. Giuliani, C. Nones, M. Pedretti, S. Sangiorio, Surface-sensitive macrobolometers for the identification of external charged particles, *Appl. Phys. Lett.* **86** (2005) 134106.
- [47] L. Foggetta, et al., Composite macro-bolometers for the rejection of surface radioactive background in rare-event experiments, *Astropart. Phys.* **34** (2011) 809–821.
- [48] A. Strumia, F. Vissani, Implications of neutrino data circa 2005, *Nucl. Phys. B* **726** (2005) 294–316.
- [49] G. L. Fogli, et al., Observables sensitive to absolute neutrino masses (Addendum), *Phys. Rev. D* **78** (2008) 033010.